An Alternative to Spinning Dust for the Microwave Emission of LPH 201.663+1.643: an Ultracompact H II Region

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ABSTRACT

The microwave spectral energy distribution of the dusty, diffuse H II region LPH 201.663+1.643 has been interpreted by others as tentative evidence for microwave emission from spinning dust grains. We present an alternative interpretation for that particular object; specifically, that an ultracompact H II region embedded within the dust cloud would explain the available observations as well or better than spinning dust. Parameters for the size, surface brightness, and flux density of the putative ultracompact H II region, derived from the microwave observations, are within known ranges. A possible candidate for such an ultracompact H II region is *IRAS* 06337+1051, based upon its infrared colors. However, *IRAS* 06337+1051's infrared flux appears to be too small to be consistent with the microwave flux required for this alternative model to explain the observations.

Subject headings: cosmic microwave background — diffuse radiation — dust, extinction — ISM: clouds — H II regions — radiation mechanisms: thermal — radio continuum: ISM

1. Introduction

Studies of the cosmic microwave background are affected by foreground emissions from the Milky Way and other sources. Principal mechanisms are thermal emission from warm dust, synchrotron from electrons gyrating in magnetic fields, and free-free (a.k.a. bremsstrahlung) emission from ionized plasma. An elusive forth foreground is attributed to spinning dust (Draine & Lazarian 1998a) or perhaps magnetic dust (Draine & Lazarian 1999). A small

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but growing number of statistical comparisons of infrared tracers of dust and microwave observations of "CMB quality" have demonstrated repeatedly, but in each case at low significance, an excess of microwave emission, correlated with dust on the sky, and possibly due to spinning or magnetized dust. Finkbeiner *et al.* (2002, Paper I) list such statistical comparisons and add to them two tentative detections of the spinning-dust mechanism in specific astronomical sources, LPH 201.663+1.643 and Lynds 1622, from a sample of 10 sources observed by them.

LPH 201.663+1.643 is the topic of this *Letter.* It differs from the other nine dust clouds observed by Finkbeiner *et al.* (2002) in that it is known to be a diffuse H II region whereas the others are not ionized. Finkbeiner *et al.* included LPH 201.663+1.643 in their sample despite their prejudice that free-free emission might overwhelm any emission from spinning dust. Alternatively, one might anticipate that ionized regions would be good places to find microwave emission from spinning dust, because in those regions, ion collisions with grains are expected to be the largest contributory factor by far in maintaining the spin of the grains (Draine & Lazarian 1998b).

Because of its special status as the sole H II region in the list, and because LPH 201.663+1.643 provided the only very significant detection and was indeed much brighter than the spinning-dust theory would have predicted, we thought that a different explanation might exist. The alternative model for LPH 201.663+1.643 that we present in this *Letter* is the superposition of one source with very large emission measure and very small angular scale with a low emission-measure, extended source. The combination of a small, optically thick source and a large optically thin source, both emitting by free-free, can create the rising microwave spectrum observed in Paper I.

2. Observations

The three observations from Table 3 of Paper I relevant to this *Letter* are $I_\nu = 0.397 \pm 0.046$, 0.516 ± 0.019, and 0.667 ± 0.027 MJy sr^{-1} at $\nu = 5$ GHz, 8.25 GHz, and 9.75 GHz. Note that the brightness increases with frequency.

The envelopes of newly forming stars in close proximity to an O-type star can have emission measures as large as 3×10^8 cm^{-6} pc over angular scales $\lesssim 1''$ (McCullough *et al.* 1995). An ensemble of externally ionized stellar envelopes could match the angular extent of the dust cloud, but the combined flux from the ensemble would be insufficient to match the observed microwave flux from LPH 201.663+1.643 which at 9.75 GHz is ~ 3 Jy. For example, the total 15 GHz flux density from the the ensemble of 24 ionized envelopes illuminated by

θ^1C Orion is 0.175 Jy (Felli *et al.* 1993). A better idea would be an ultracompact H II region, which would intercept all of the UV flux from an OB star, whereas an ensemble of stellar envelopes intercepts only a tiny fraction of the OB star's flux.

In order to estimate the distance to LPH 201.663+1.643 we searched its vicinity in the SIMBAD database for hot stars that could ionize it and found two, GSC 00737-01170 (O5:; V=11.29; B-V=0.75) and GSC 00737-00898 (O5; V=10.27; B-V=1.11), where the spectral types and magnitudes are from Voroshilov *et al.* (1985). For an O5 V star, $\mathrm{M_V} = -5.3$ and for an O5 Ia star, $\mathrm{M_V} = -6.4$ (Vacca, Garmany, & Shull 1996). Regardless of luminosity class, an unreddened O5 star has B-V = -0.33 (Cox 2000). For $A_V = 3.2E(B-V)$, the implied distances to GSC 00737-01170 and GSC 00737-00898 are 4.2 kpc and 1.6 kpc, respectively if each is O5 V, and 7.0 kpc and 2.6 kpc, respectively if each is O5 Ia. At $l = 201.6^\circ$ and $b = +1.6^\circ$, LPH 201.663+1.643 is $\sim 22^\circ$ from the anticenter direction, and its Galactic height $Z < 200$ pc for d < 7.0 kpc.

3. Modeling

The optical depth for free-free emission,

$$\tau_{\rm ff} \approx 2.6\ \mathrm{T_4^{-1.35}}\ (\mathrm{EM}/10^9\ \mathrm{cm^{-6}\ pc})\ (\nu/10\ \mathrm{GHz})^{-2.1}, \tag{1}$$

where $\mathrm{T_4} \equiv \mathrm{T_e}/10^4\mathrm{K}$, $\mathrm{T_e}$ is the electron temperature, EM is the emission measure, and ν is the radio frequency. As observed with an antenna of beam solid angle Ω, the apparent microwave surface brightness of a uniform disk of radius θ_s is

$$\mathrm{I_1} = \mathrm{B_\nu(T_e)}(1 - \mathrm{e}^{-\tau_{\rm ff}})\pi\theta_{\rm s}^2\Omega^{-1} \tag{2}$$

where $\mathrm{B_\nu(T_e)}$ is the Planck function and we assume that the background is negligible and that $\pi\theta_s^2 << \Omega$. For the 140-foot antenna, $\Omega = 4.59, 1.75,$ and 1.31 microsteradians for observing frequencies of 5 GHz, 8.25 GHz, and 9.75 GHz respectively, but in our model we use $\Omega = 4.59 \times 10^{-6}$ sr for all frequencies because in Paper I the higher frequency data were smoothed to match the 5 GHz beam.

To get the total emission of the model, we add $\mathrm{I_1}$ to the free-free emission from a diffuse, optically thin component. The diffuse component cannot be very diffuse, because if it was larger than the 0.2° chop used in Paper I at 8.25 and 9.75 GHz, it would be eliminated by the chopping. Although we do not know the angular distribution of free-free emission in this region, we assume that the diffuse free-free component contributes to the brightnesses at each frequency equally except for the $\nu^{-0.1}$ spectral index of optically thin free-free. Thus,

our model is

$$I_\nu = I_2(\nu/5\ \mathrm{GHz})^{-0.1} + B_\nu(T_e)(1 - e^{-\tau_{ff}})\pi\theta_s^2\Omega^{-1}, \quad (3)$$

where the model parameters are I_2 and the two parameters of the ultracompact H II region (its radius θ_s and its emission measure, EM).

Fig. 1 compares the observed brightnesses to those predicted by the model with a few combinations of parameters for illustration. Fig. 2 illustrates χ^2 contours in the phase space of the parameters of the ultracompact H II region, θ_s and EM, with I_2 fixed at 0.255 MJy sr^{-1}. The allowed parameters are similar to those of known ultracompact H II regions (Wood & Churchwell 1989b). For EM $= 10^9$ cm^{-6} pc, $\theta_s = 1''$, the number of ionizing photons required to power the ultracompact H II region, $N_c' \gtrsim 4 \times 10^{47}(d/1\ \mathrm{kpc})^2\mathrm{s}^{-1}$ (Kurtz, Churchwell, & Wood 1994), which corresponds to a main-sequence spectral type B0 or earlier for $d = 1.6$ kpc or O8 or earlier for $d = 4.2$ kpc (Vacca, Garmany, & Shull 1996).

4. A Possible Candidate: *IRAS* 06337+1051

IRAS 06337+1051 stands out in the *IRAS* ISSA images as the brightest 25 μm source in the vicinity of LPH 201.663+1.643. *IRAS* 06337+1051 has the infrared colors of an ultracompact H II region (Fig. 3). Its PSC position (Beichman *et al.* 1988), $6^{\mathrm{h}}36^{\mathrm{m}}29^{\mathrm{s}}.47$ $+10°49'5''.1$ [2000], with an error ellipse $38''\times7''$ oriented with the major axis at a position angle of 94°, is compatible with the Paper I's linear scans, which were centered on $6^{\mathrm{h}}36^{\mathrm{m}}40^{\mathrm{s}}$ $+10°46'28''$ and oriented at position angle 292.5°. The nominal scan's closest approach to the PSC position of *IRAS* 06337+1051 is 1.4′, and the peak along the nominal 8.25 GHz scan occurs 2.4′ or 0.6′ east of the nominal position of *IRAS* 06337+1051, for the forward and reverse scan directions respectively (Paper I, Fig. 3b). For comparison, the resolution (FWHM) of the microwave data was 6′. The antenna temperature at 8.25 GHz of the ultracompact H II region is $\lesssim$55% of the total for the models in Section 3, so the peak position at 8.25 GHz need not be centered at the position of the ultracompact H II region.

A potential flaw in *IRAS* 06337+1051 as the putative ultracompact H II region is that our model requires parameters for the ultracompact H II region that would make it brighter than most ultracompact H II regions at radio wavelengths (cf. Wood & Churchwell 1989a and Kurtz, Churchwell, & Wood 1994) but at 60μm *IRAS* 06337+1051 is four times fainter than the median of embedded OB star candidates selected by Wood & Churchwell (1989a). For the models depicted in Fig. 2, the ultracompact H II regions' flux density, $F_\nu(2cm)$ ranges from 1.6 Jy to 4.4 Jy. Ultracompact H II regions are more than a thousand times brighter in the infrared than in the radio (Kurtz, Churchwell, & Wood 1994), so the 3σ upper limit to the *IRAS* PSC flux at 100 μm, $F_\nu(100\mu\mathrm{m}) < 383$ Jy would imply that the radio flux density

$F_\nu(2cm) < 0.4$ Jy, i.e. in conflict with the model fluxes. Stated another way, the luminosity is

$$L_* = 4\pi d^2 S_\nu \Delta\nu f_\nu^{-1}, \tag{4}$$

where f_ν is the fraction of total luminosity L_* emitted at frequency ν in the passband $\Delta\nu$, and S_ν is the associated flux density. For *IRAS* 06337+1051 at 60 μm, $S_\nu = 33$ Jy, $\Delta\nu = 2.58 \times 10^{12}$ Hz (Beichman et al. 1988), and $f_{60\mu\mathrm{m}} = 0.25$ for ultracompact H II regions (Wood & Churchwell 1989a), so $L_* = 100(d/1kpc)^2 L_\odot$. Because ionizing OB stars have $L_* > 10^4 L_\odot$, the implied distance $d > 10$ kpc. At such large distances from the Galactic center, massive stars do exist but are rare (de Geus *et al.* 1993). However, if the distance to *IRAS* 06337+1051 $d > 10$ kpc, then it is too far behind LPH 201.663+1.643 for them to be physically associated, and their alignment would be highly improbable *a priori*.

5. Conclusions

An optically thick ultracompact H II region can provide a rising microwave spectrum with a spectral index ≈ 2 which is similar at these frequencies to the spinning-dust model's spectral index ≈ 2.8 (Ferrara & Dettmar 1994; Draine & Lazarian 1998b). For free-free emission, for $\tau_{ff} \gtrsim 1$ at $\nu \lesssim 10$ GHz, the EM must be $\gtrsim 10^9$ cm^{-6} pc.

While *IRAS* 06337+1051 is within a fraction of a 6′ beam width of LPH 201.663+1.643, and has the infrared colors of an ultracompact H II region, its *IRAS* fluxes are too small unless its distance is improbably large. Also, the distance-independent ratio of the 100 μm flux of *IRAS* 06337+1051 to our model's 2-cm flux is too small by more than an order of magnitude. The latter conflict is mitigated somewhat if the star is an early B-type star that has an atypically large ratio of ionizing to bolometric luminosity as has been observed in some cases (Cassinelli 1996) and has been predicted by modern stellar atmosphere models (Vacca, Garmany, & Shull 1996).

Paper I concluded that "as long as the density is low, as in the LPH list, H II regions may be optimal targets for future work for DASI, CBI, and *MAP*." It would be inappropriate to misinterpret this single case study of LPH 201.663+1.643 as contradictory to that recommendation. Instead, attention to its premise, that the density be low, is especially appropriate. The all-sky observations made by *MAP* will allow astronomers to conveniently avoid any regions that might be unsatisfactory in that regard.

The hypothesis presented in this *Letter* can be tested directly with radio interferometric imaging, which we plan to complete in early 2002. If that test shows not even one dense ionized knot in LPH 201.663+1.643, then this *Letter*'s remaining value will be the analysis

of Section 3, and the microwave emission from LPH 201.663+1.643 will still be a mystery.

We thank Doug Finkbeiner for sending us a pre-publication manuscript that initiated our thoughts about LPH 201.663+1.643. A conversation with Bruce Draine during his visit to Illinois on October 30, 2001, was especially helpful; as referee, B. D. made additional valuable comments, most importantly that *IRAS* 06337+1051 be in its own section.

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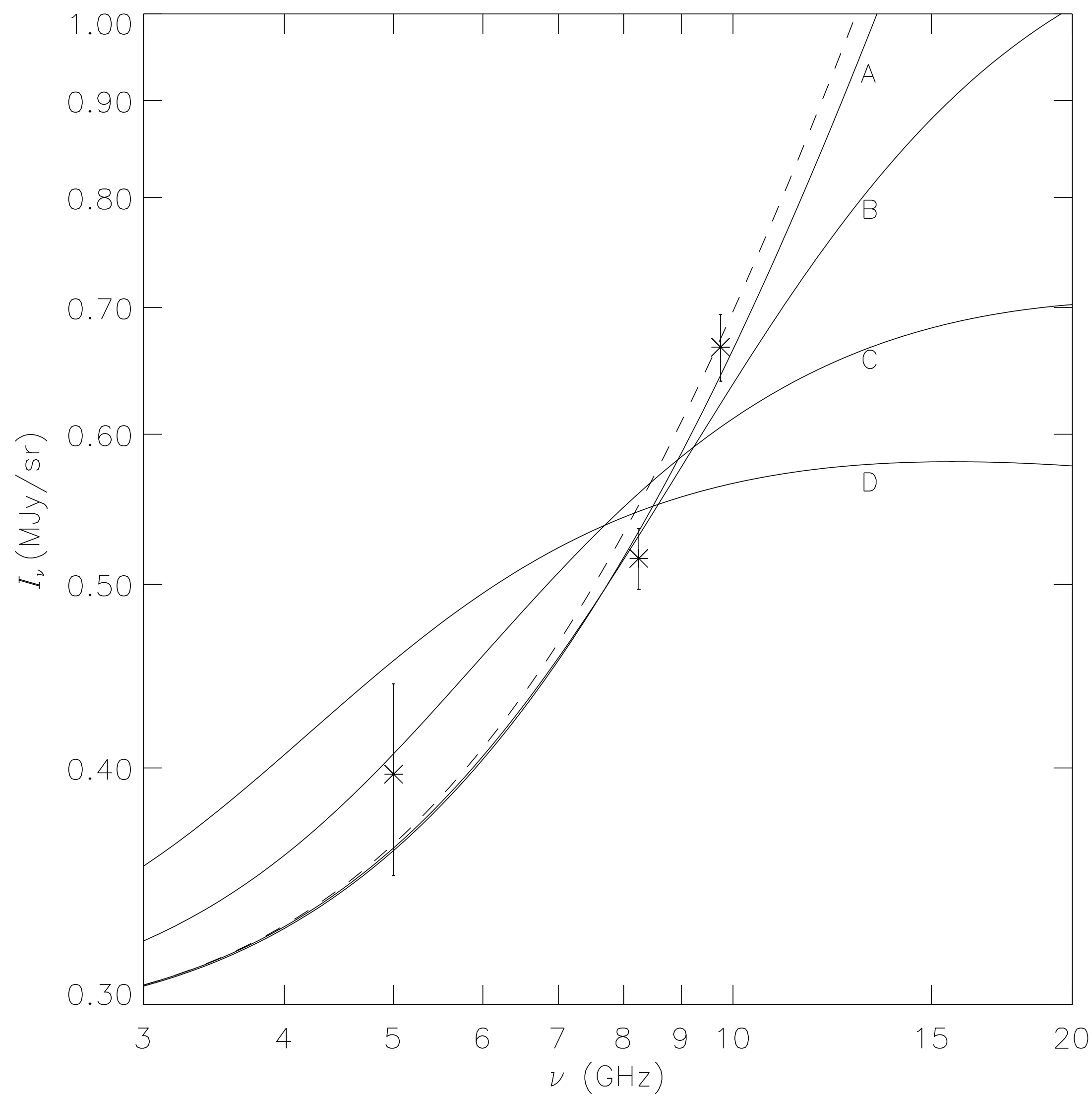
Fig. 1.— The brightness of LPH 201.663+1.643 at three microwave frequencies (Paper I) is compared to that of combined emission from a diffuse H II region and an ultracompact H II region (Equation 3) for various model parameters (solid lines). For models A, B, C, and D respectively, with $\theta_{\rm s}$ and EM as indicated in Fig. 2, and $I_2 = 0.255$ MJy sr^{-1} in all four models, the $\chi^2 \approx 2, 4, 10,$ and 20. The dashed line shows model A with the additional contribution from spinning dust appropriate for a warm ionized medium (Ferrara and Dettmar 1994; Draine & Lazarian 1998b) and a dust column N(H) $= 2.7 \times 10^{22}$cm^{-2} (Paper I).

Fig. 2.— Contours of χ^2 are plotted in the phase space of the parameters of the ultracompact H II region, θ_s and EM, for a representative value for the parameter that describes the diffuse H II region $I_2 = 0.255$ MJy sr^{-1}. For values of EM $\gtrsim 10^9$ cm^{-6} pc, the ultracompact H II region is optically thick at even the highest observed frequency, so the χ^2 contours are open at the top of the plot. Models with $\theta_{\rm s}$ and EM as indicated by the letters A, B, C, and D are compared to the data in Fig. 1.

Fig. 3.— *IRAS* 06337+1051 is compared to known ultracompact H II regions (*filled circles*) in an *IRAS* color-color plot from Wood & Churchwell (1989a). Two solid-lined rectangles are centered on the most-likely colors of *IRAS* 06337+1051, $\mathrm{Log}(F_\nu(25\mu m)/F_\nu(12\mu m)) = 0.96 \pm 0.049$, and $\mathrm{Log}(F_\nu(60\mu m)/F_\nu(12\mu m)) = 1.59 \pm 0.094$. The smaller rectangle has a 1σ half-width and half-height; the other rectangle is three times larger. That the rectangles lie in the region of the diagram populated by ultracompact H II regions and that other types of sources very rarely populate that region make *IRAS* 06337+1051 likely to be an ultracompact H II region. The dashed lines indicate the boundary prescribed by Wood & Churchwell (1989a) to discriminate embedded OB stars from other sources in the *IRAS* point source catalog. Other representative sources are those within a $2^\circ \times 2^\circ$ box in the Galactic plane (*open squares*) and a group of *IRAS* sources that lie between $13^{\rm h}00^{\rm m}$ and $13^{\rm h}10^{\rm m}$ in right ascension (*crosses*).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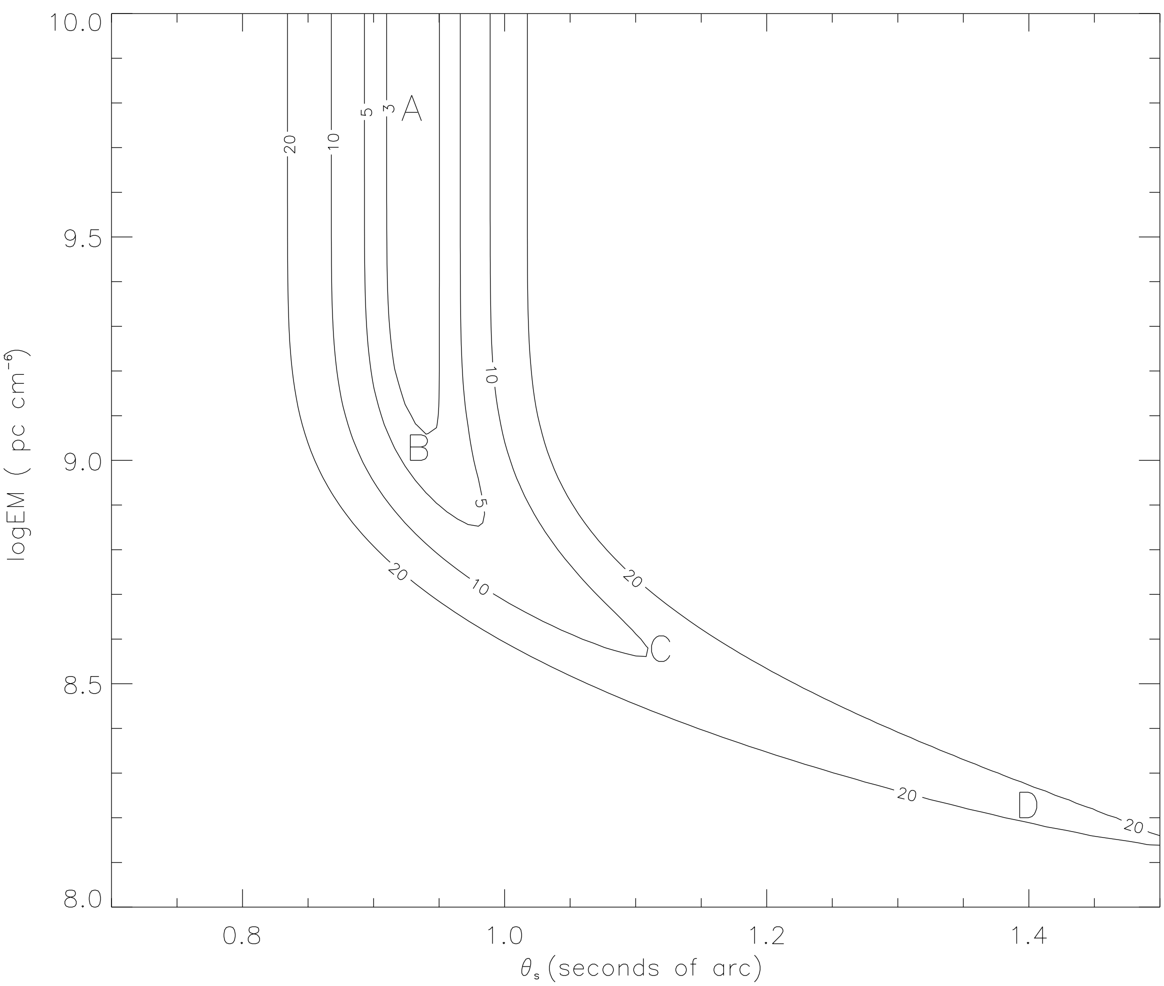
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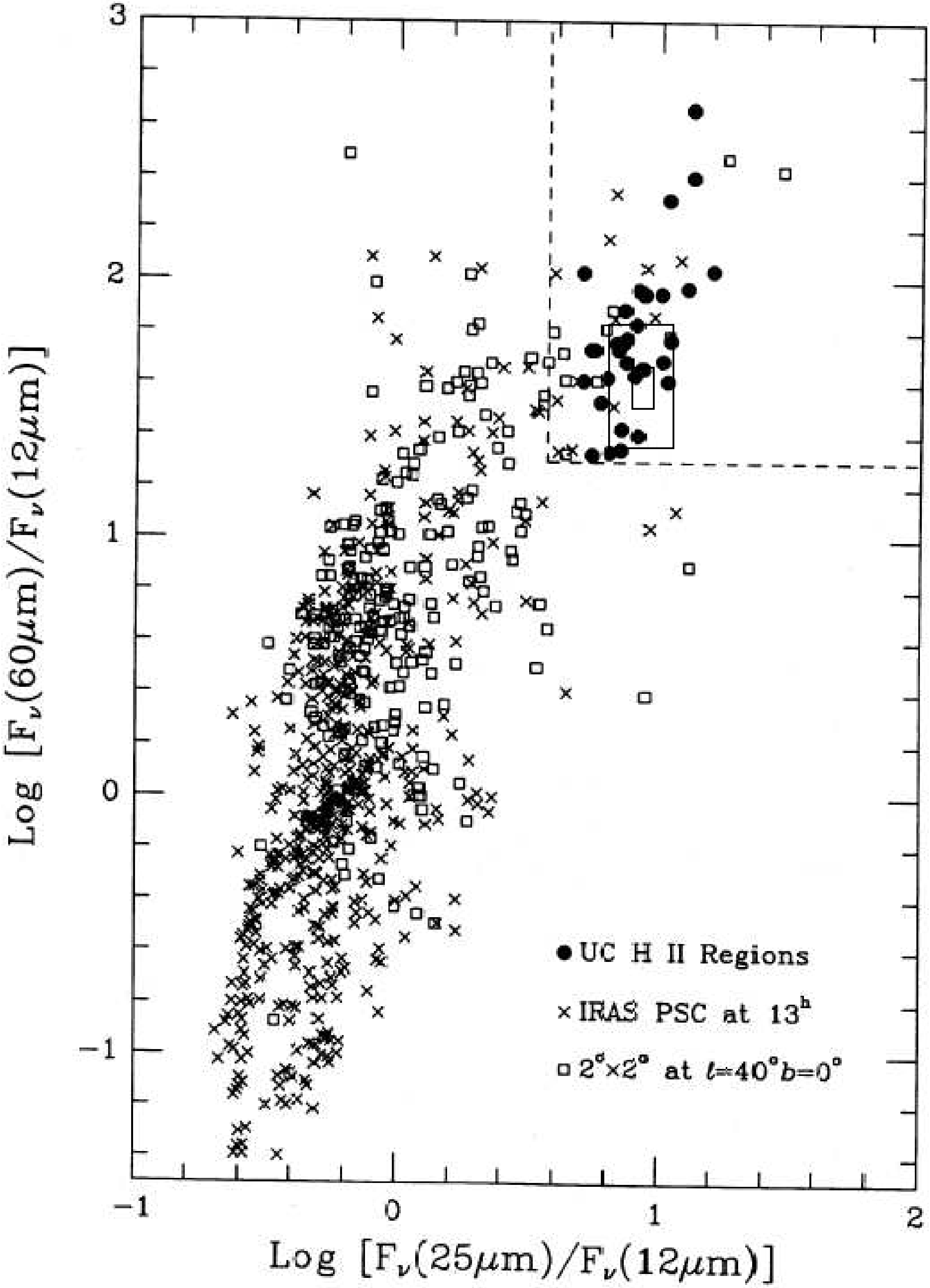

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Log [F$_\nu$(60μm)/F$_\nu$(12μm)]
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UC H II Regions
IRAS PSC at 13^h
2°×2° at l=40° b=0°